ENVIRONMENTAL CONTAMINATION: Dynamic Sampling for Assessment and Remediation of Volatile Organic Compounds--The Membrane Interface Probe

A SunCam Online Continuing Education Course

By
Mary Anna Evans, M.S., P.E., and
Kelly Bergdoll, President, KB Mobile Laboratories

Introduction

This course is intended for engineers, geologist, scientists, and technicians who supervise and conduct field investigations intended to detect and delineate contaminated volumes of soil and groundwater. It will be useful to those who are new to contamination assessment, but those who are experienced in environmental work should find the information useful, simply because of the ongoing technical advances in this field.

A few short years ago, the technology to retrieve vapor samples at depth, without collecting soil or groundwater samples and bringing them to the surface, did not exist. Continuing education courses like this one can keep practicing engineers and scientists abreast of strategies like dynamic sampling and technologies like the membrane interface probe that have the potential to save time, money, and effort, while providing superior results.

Overview of contamination assessment and remediation

Remediation of a contaminated site is a complex problem that is best approached in a stepwise manner. Rushing into remediation without adequately characterizing site conditions can be disastrous. The most technically advanced and expensive remedial strategy cannot work if it is the wrong strategy for the site. Yet site characterization is an expensive

proposition in terms of time, labor costs, equipment costs, and laboratory fees.

A careful project manager will evaluate each step in the process for opportunities to improve efficiency. In a conventional site assessment, those steps generally include the following activities—

- **Initial site visit—**An environmental consultant generally becomes involved at a site when there is some reason to be concerned that contamination might exist. An observer might note an odor or free product that suggests possible contamination of water or soil. Alternatively, previous activities on the site might have occurred that are known to be associated with contamination.

The consultant would assess the potential for contamination by interviewing knowledgeable individuals and reviewing maps, photographs, and documents related to contaminants used on-site. A thorough site inspection would be used to ground-truth the information gained from documents and interviews. Using this data, the consultant would offer an opinion on whether there is a reasonable potential for significant site contamination. If so, the opinion would also indicate the most likely contaminants and the locations where those contaminants would most likely be found.

- **Initial site testing—**If the initial visit found a reasonable potential for site contamination, a field team would then be mobilized to investigate that potential. This field effort would serve as a screening step—is there contamination at the locations deemed to have the biggest potential for a problem? If not, the presumption would be that significant contamination does not exist.

- **Contamination assessment—**A sampling plan would be developed based on findings from the initial site testing. The goal of this effort would be to define the severity and extent of the contamination in all three dimensions. If an adaptive, dynamic sampling approach is not in place, multiple field efforts can be required to define a plume that extends to an unexpected distance in one or more dimension

- **Remedial design—**Information obtained from the contamination assessment is used to develop a strategy for remediating known contamination, then to design the equipment and specify the field activities necessary to implement that strategy.

- **Remediation implementation—**A field team mobilizes and, where appropriate, installs the equipment necessary to implement the remedial design. Site testing is also required

during this stage to confirm that the design is functioning properly. For example, samples might be collected to insure that injected fluids are moving as expected in the subsurface.

- **Operation and Maintenance of the Remedial System—** Remedial designs that require equipment to remain on-site during a protracted period of remediation must be visited periodically for maintenance of that equipment. Samples are also collected at this time to assess whether the contaminant levels are indeed decreasing.

- **Monitoring--**.The remedial design will specify the contaminant concentration level at which remediation can be considered completed. When these levels are reached, periodic sampling will continue until the desired levels are maintained for a specified period.

Repeated field mobilizations are clearly a large part of the labor costs for remediating a contaminated site. Laboratory fees for analyzing samples are generated at every step of the process after the first one. Collecting more samples than necessary adds to those costs. Collecting insufficient samples might initially save in laboratory fees, but the necessity of remobilizing the field team to collect needed data negates those savings.

Dynamic sampling offers the ability to screen contaminant levels in soil and groundwater semi-quantitatively, **while still in the field**.

Dynamic sampling virtually eliminates surprises that can occur from the traditional delay in receiving laboratory results. If contaminants are discovered in an area thought to be free of problems, the work plan can be revised dynamically, at the moment. The needed samples can be obtained during the same field effort.

Conversely, if no contamination is encountered in an area where it is expected to exist, dynamic sampling can help avoid the costs incurred in analyzing unnecessary samples.

This dynamic sampling and semi-quantitative analysis also helps the project manager select which samples to submit to an analytical laboratory for confirmatory testing. The number of analyses which yield little new information, yet still generate laboratory bills, can be greatly reduced.
It is instructive to compare traditional contamination assessment methods with the streamlined approach made possible with dynamic sampling.

Traditional Contamination Assessment Methods	Dynamic Sampling
1. Initial site visit—determine need for testing	1. Initial site visit—determine need for testing and develop conceptual model for sampling effort
2. Initial site testing—use laboratory data as screening method to plan future field efforts	2. Initial site testing—refine conceptual sampling plan to assess contamination and develop remedial plan based on in-the-field results, obtaining necessary data in one field effort
3. Contamination assessment—conduct one or more sampling efforts to delineate extent and severity of contamination	
4. Remedial design—prepare remediation plan based on knowledge of extent and severity of contamination	3. Remedial design—prepare remediation plan based on knowledge of extent and severity of contamination proven by implantation of conceptual plan
5. Remediation implementation—install system specified in remedial design and obtain samples to assess performance	4. Remediation implementation—install system specified in remedial design and do in-the-field testing to assess performance
6. Revise remediation strategy if laboratory data indicates a need	
7. Operation and Maintenance—ensure that equipment continues to operate as designed	5. Operation and Maintenance—ensure that equipment continues to operate as designed
8. Monitoring—Obtain periodic samples to ensure target contaminant levels are maintained	6. Monitoring—Obtain periodic samples to ensure target contaminant levels are maintained

Table 1. Comparison of the Effect of Dynamic and Traditional Sampling Methods on Contamination Assessment and Remediation

Dynamic sampling and analysis provides the project manager with information that can save time, effort, and money.

Introduction to dynamic sampling

Hard experience has taught many engineers that a remedial design is only as good as the accuracy of the conceptual site model used to develop that design. In order for any remediation system to be effective, a thorough understanding of the subsurface environment, including contaminant mass and hydrogeologic conditions, is imperative. Discounting dumb luck, an incomplete site characterization will inevitably lead to an unsuccessful remediation.

The EPA's Triad approach outlines the use of a dynamic sampling plan to expedite thorough characterization of a contaminated site.[1] This strategy increases the likelihood of a successful remediation, resulting in long-term cost savings.

In TRIAD-based projects, the investigation would be guided by a conceptual site model (CSM), a plan that includes a decision pathway or flowchart that dictates adjustments to the sampling plan and CSM as real-time data comes in. When enough data has been collected to assure a

valid CSM, the remedial design is implemented and the real-time data can be used again during the remediation process as a diagnostic tool.

A key component of the dynamic sampling approach is the use of **real-time measurement systems (RTMS)** that provide the geologist or engineer with data almost instantly, and in sufficient quantity to provide a level of sampling density that assures data quality.

Real-time, accurate data enable decisions regarding the sampling effort to be implemented onsite, where dynamic decisions are best made. Collecting and managing data in real time provides a means of building a thorough picture of subsurface contamination and subsequently providing the information necessary to design an effective remediation system.

The use of direct sensing probes that can provide both contaminant and lithologic information in real time allows for targeted sampling efforts. These probes enable the design engineer to focus the application of injection chemicals with precision, and they allow onsite monitoring of injection efforts during and after treatment. All these advantages lead to a more successful remediation and potentially huge cost savings over the life of the project.

Gathering enough information to develop an accurate conceptual site model is an unavoidable part of remediation design. The nature of subsurface contamination dictates that the designer will always be “working blind.”

Life would be far easier if the field team could simply roll back a few feet of soil and look at the underground situation. Since that is impossible, assessment of existing contamination will always involve extrapolating a plausible contaminated volume based on a discrete number of samples. In other words, the design depends on conceptual modeling.

Because site geology and contamination are naturally heterogeneous, they both limit our ability to adequately characterize a site with so-called "representative samples." The possibility of missing critical information such as a permeable layer of soil routing contaminants into unanticipated areas is very real. Even if representative sampling reveals this type of complication, returning to the field to collect samples that weren't anticipated when developing the budget is an expensive endeavor.

Gathering information in real time with probes that give discrete information at depth addresses some of these limitations. Combinations of direct sensing tools that provide information on the presence and extent of contamination are invaluable in deciphering subsurface conditions.

Dynamic Sampling with the membrane interface probe (MIP)

Patented and developed by Geoprobe® Systems in the mid-1990s, **the MIP is a powerful high-resolution screening tool capable of providing both volatile organic contaminant and soil conductivity data in real time.** The MIP provides a real-time vertical log of volatile organic contamination with depth.

Since the MIP probe also contains an electrical conductivity sensor, it provides insight into potential contaminant migration pathways with lithologic information that can be interpreted from the soil conductivity data. The MIP is a primary tool for the assessment of chlorinated solvent contamination and can also be used for detecting light petroleum constituents.

Figure 1. MIP and DPT in action. Direct push rig is on the left and a data acquisition vehicle housing the MIP field computer and GC detectors is on the right.

Photo Courtesy of KB Labs

How the MIP works

The key component of the probe is a semi-permeable membrane that acts as an interface between subsurface contaminants and gas phase detectors arrayed at the surface. The membrane is seated in a heated block attached to the probe that accelerates diffusion of volatile compounds across the membrane.

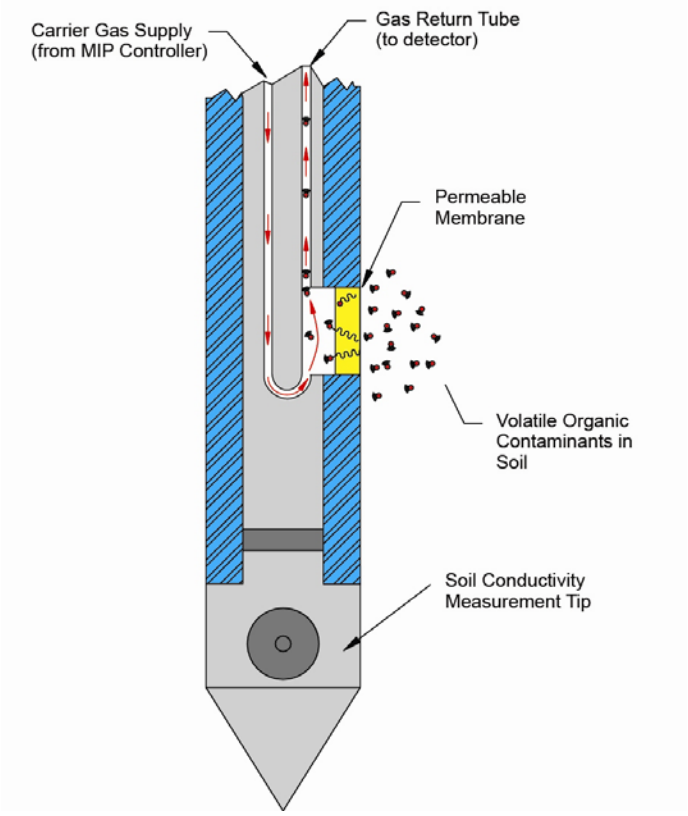

Figure 2. Line drawing of the MIP probe

MIP probe drawing courtesy of Geoprobe® Systems

The membrane is heated to a nominal temperature of 120 degrees C. Carrier gas is circulated across the internal surface of the membrane, carrying volatiles that have diffused across the surface of the membrane to the surface for analysis by gas phase detectors.

The contaminants travel up a trunk line that is threaded through the direct push rods and into the gas phase detectors, producing a signal at the surface. Detector signal data is acquired continuously, though the normal practice is to advance the probe in one-foot intervals at a travel time that has been established for the contaminant of interest.

A depth-measuring potentiometer referred to as the “stringpot” is mounted to the direct push machine and transfers a voltage to the data acquisition system for accurate depth measurement below ground surface.

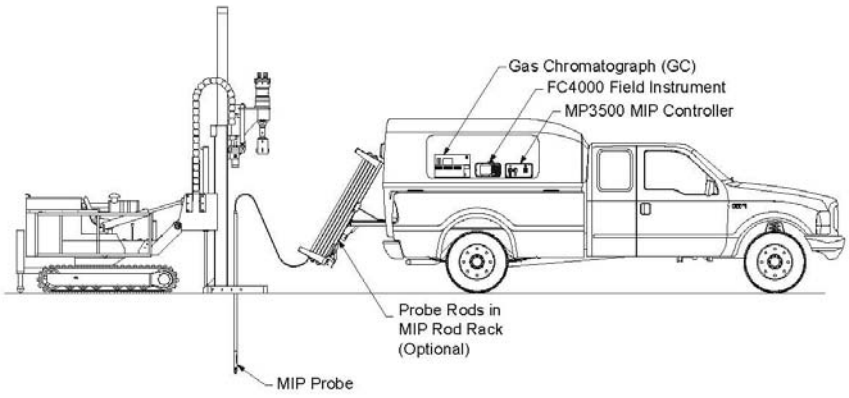

Figure 3. Typical configuration of DPT and MIP

Drawing courtesy of Geoprobe® Systems

The detector configuration used by most MIP service providers is a combination of **photoionization (PID), flame ionization (FID),** and **electron capture (ECD).** This configuration allows use of the system to detect and group responses for chlorinated solvents, non-chlorinated volatile aromatic hydrocarbons (BTEX),

BTEX is a commonly used acronym for non-chlorinated volatile aromatic hydrocarbons, because the compounds most commonly detected are **b**enzene, **t**oluene, **e**thylbenzene, and **x**ylene.

and straight-chain hydrocarbons such as methane. Detection limits are roughly 100 **parts per billion (ppb)** for chlorinated compounds if an ECD detector is used, and 1 **part per million (ppm)** for BTEX compounds with the PID detector. The results are reported as responses, rather than in units of concentration, so the method is considered semi-quantitative. A brief discussion of the detectors follows:

- **Photoionization Detector (PID):**
  The PID uses ultraviolet radiation to ionize molecules in the MIP carrier gas stream for analyte detection. Since the PID is a non-destructive detector, it can be used in series with other detectors. This detector will detect aromatic hydrocarbons, such as benzene or toluene, as well as multiple bonded chlorinated

compounds, such as trichloroethylene and perchloroethylene as well.

This detector is generally used for the detection of aromatic hydrocarbons, such as benzene or toluene, but it can detect chlorinated compounds as well. The detection limit for aromatics is much lower than for chlorinated compounds, and all compounds to be detected must have an ionization potential within the range of the lamp used in the PID.

- **Flame Ionization Detector (FID):**

  The FID uses a hydrogen/air flame to produce ions and electrons, which conduct electricity through the flame. A potential is applied across the flame burner tip and a collector electrode, and the resulting current is measured.

  The FID is most sensitive for volatile aliphatic hydrocarbons and high carbon compounds such as methane and propane. Although not generally thought of as a detector for chlorinated solvents, it can actually detect chlorinated compounds present in extremely high levels and is useful in a situation where a denser-than-water non-aqueous phase liquid (DNAPL) is encountered and the more sensitive detector responses are already maximized.

- **Electron Capture Detector (ECD):**
  The ECD passes the carrier gas over a beta-emitter, causing ionization and electron production. If molecules are present that will capture electrons, the current will decrease and this decrease is measured.

  The ECD is a selective detector and highly sensitive to electronegative groups such as halogens and peroxides. Since the ECD is selective, a response in the field by the ECD detector is a clear indication of the presence of a chlorinated compound. The ECD is also the most sensitive detector.

The MIP output is a log of the detector responses, the temperature of the heated probe, the speed of penetration, and the **electrical conductivity (EC)** by depth.

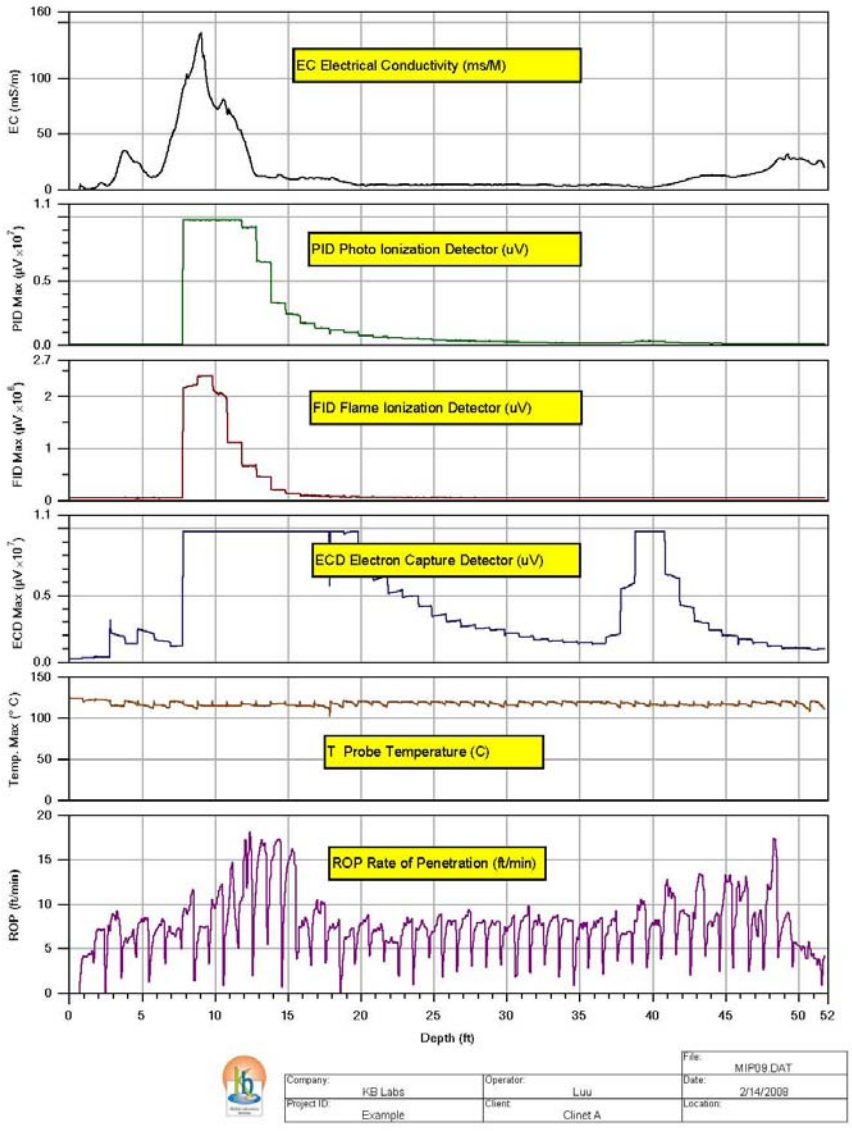

Figure 4. Sample MIP log output

Courtesy of KB Labs

Output similar to that demonstrated in Figure 4 would be generated in the field and visible onscreen throughout the logging process, showing the instrument's response vs subsurface depth. In this example, the top line is Electrical Conductivity (EC) response in millisiemens/meter (mS/m). Next are the individual detector (PID, FID, ECD) responses in microvolts (uV). The log displays probe temperature and rate of penetration. The output is also collected in numerical format and exported in excel for use in visualization software.

There are additional detectors that may be used, but the PID/FID/ECD array is the most widely available system. By using this combination, groups of contaminants may be separated and some semi-quantitative values may be interpreted.

For example, the ECD will generally only detect chlorinated compounds and does so at a lower detection limit than the other detectors. The ECD may "see" solvents at 100 ppb, resulting in a peak on the output. This output may reach its maximum, or "peg out" at a level such as 1000 ppb.

At this time the PID will begin to detect the solvent, and if there is enough solvent present to reach maximum detectable levels for both the ECD and PID detectors, the FID will begin to display peaks. This allows the operator to distinguish between ranges of estimated concentrations. Confirmatory sampling and quantitative analysis methods may then be used in a targeted fashion to further interpret the MIP data.

	ECD	PID	FID
Chlorinated compounds	100 ppb	500 ppb	10,000 ppm
Aromatics (BTEX) compounds	N/A	500 ppb	1000 ppm

Table 2. Detector summary: typical MIP detection limits (determined by analyte response testing

It is important to keep in mind that the MIP responses are expressed as microvolts and are not given in units of concentration, resulting in semi-quantitative output. For quantitative data, samples should be submitted to an accredited analytical laboratory, whether mobile or fixed base.

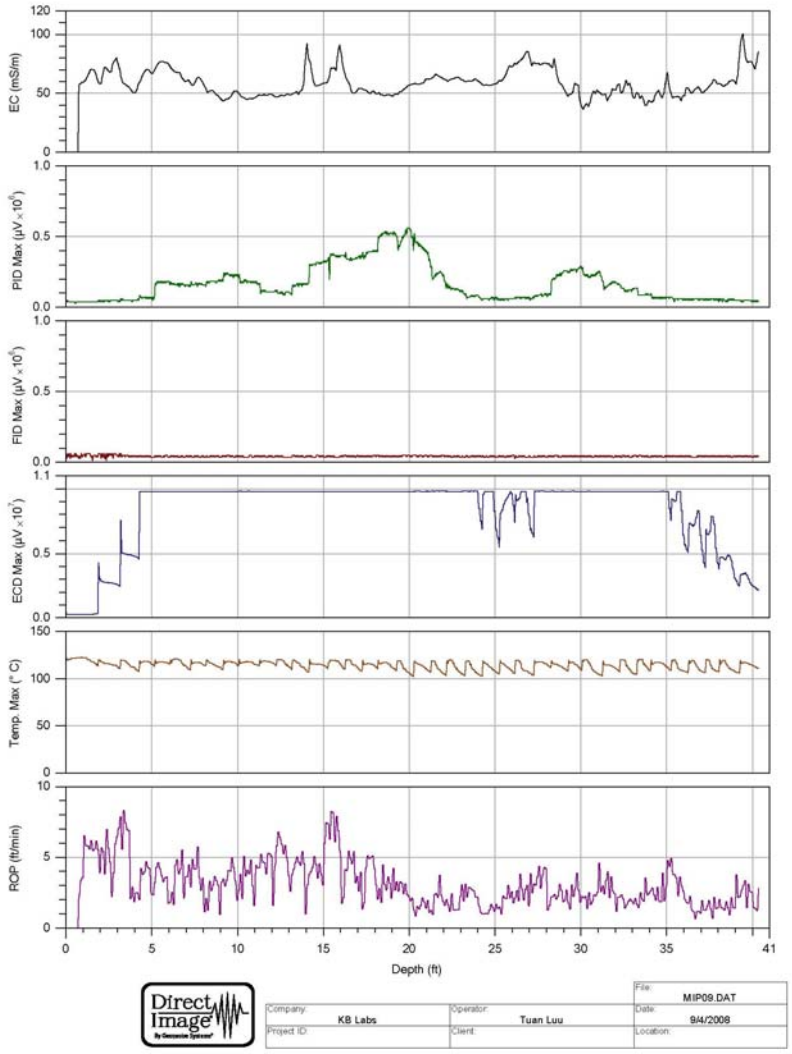

Figure 5. Log from a chlorinated solvent site
This is a log at a site primarily contaminated with TCE. Note how the ECD is able to detect the TCE first, but is quickly maximized or "pegged". The PID detector, which is much less sensitive, is providing the mapping detail showing the change in relative responses by depth, with an indication that the greatest concentration is at 20 feet. You can also see that the ECD probably has some residual or carryover towards the end of the log in the 35-40 foot interval.

Log courtesy of KB Labs

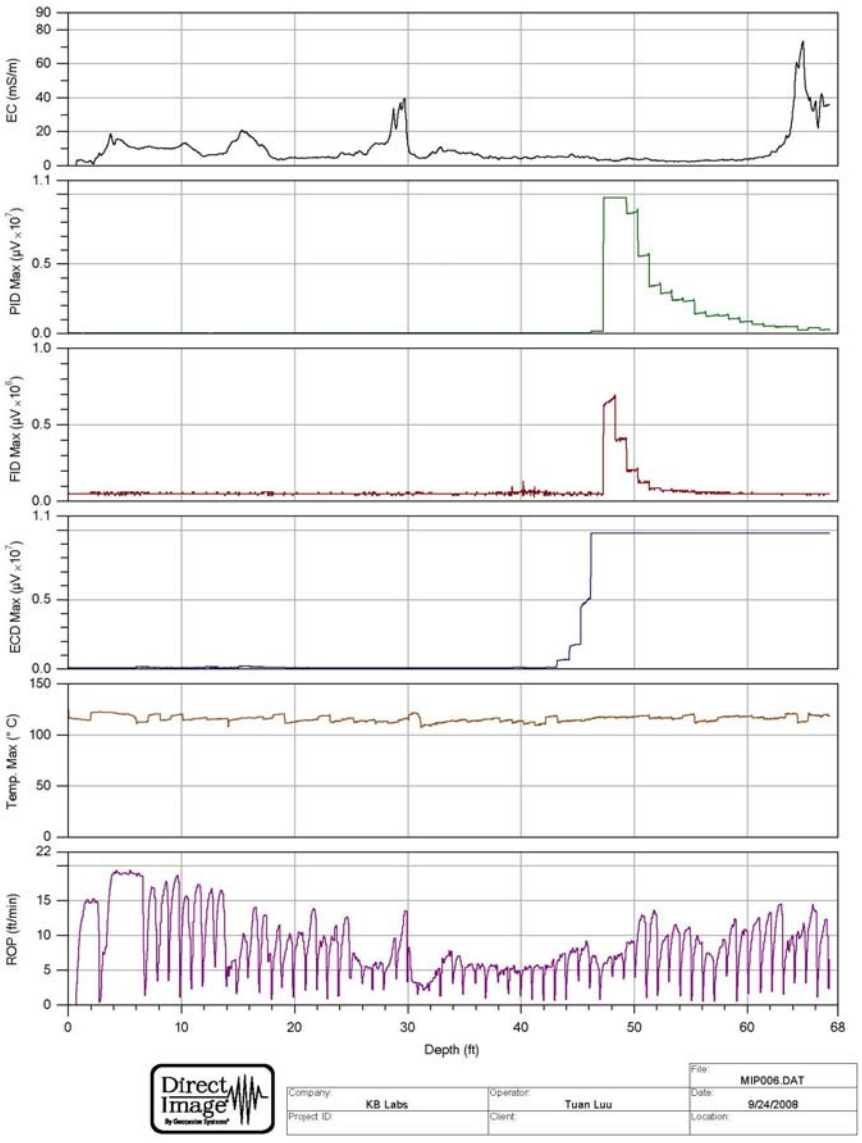

Figure 5a. Log of a DNAPL-contaminated site
In this log, not only does the ECD "peg," but the PID does, as well, and even the FID is responding. A continuous core sample was subsequently collected with visible solvent present at the 45-50 foot depth. Note how important the detection of this layer is for targeting remedial injection.

Log Courtesy of KB Labs

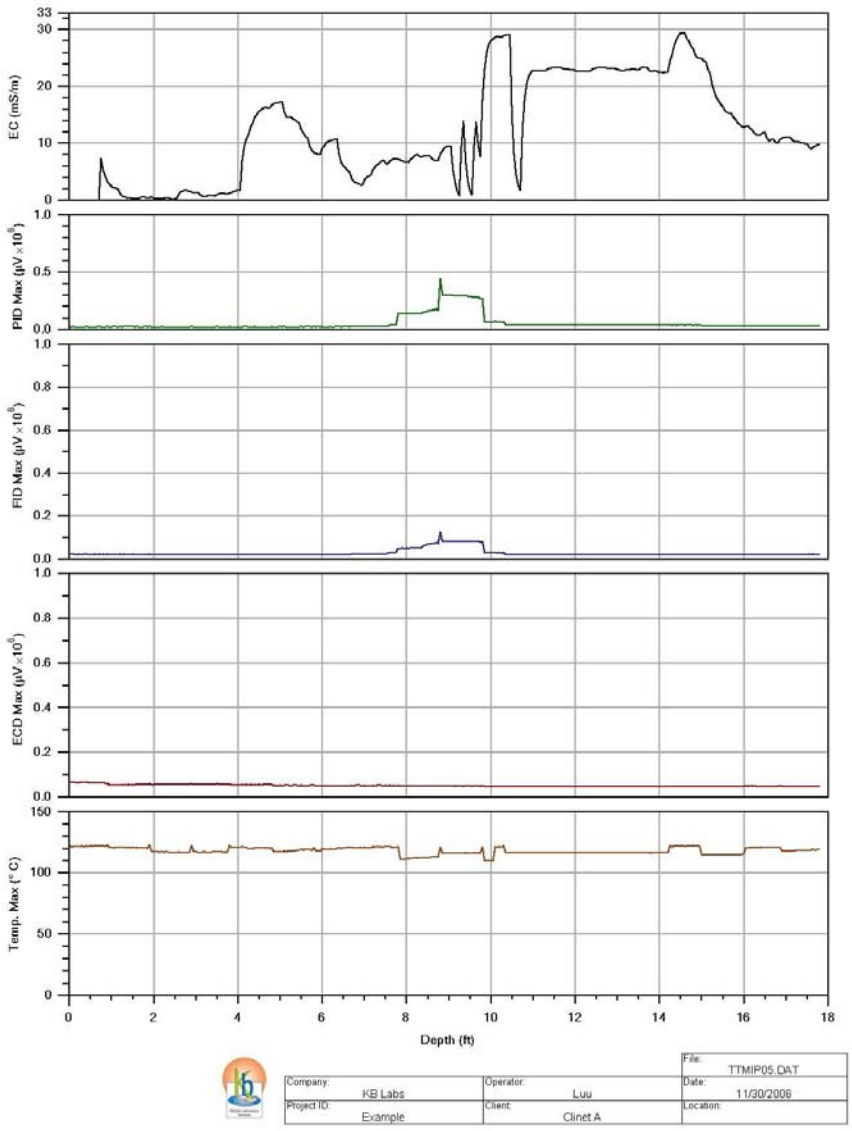

Figure 6. Log at a BTEX contaminated site
This is a log showing hydrocarbon contamination at 8-10 feet below ground surface. Note that the PID and FID detectors are showing responses, but the ECD is not. The ECD is selective to chlorinated compounds and will not respond to the petroleum components.

Log courtesy of KB Labs

Quality Assurance and Control

The **American Society of Testing Materials (ASTM)** has recently published a standard for using the MIP. The standard describes current best practices for the deployment of the MIP and quality control procedures.[2]

Response testing

One of the most important quality assurance practices is the **response test**, which is performed before each log and at the end of the day.

> The response test is a test of the working MIP system performed by placing the probe in an aqueous phase solution with a known contaminant at a known concentration.

By performing response tests, the operator can determine that the membrane is maintaining a consistent response to a known analyte and concentration and that the analytical system is performing in a stable fashion.

The response test also allows the operator to determine the trip time, which is the time required for the contaminant to penetrate the semi-permeable membrane and travel through the fixed-length trunk line to the gas phase detectors at the surface. Leaks or plugs in the membrane or elsewhere in the system can be determined by continual monitoring of the system's pressure gauges and comparing supply versus return flows.

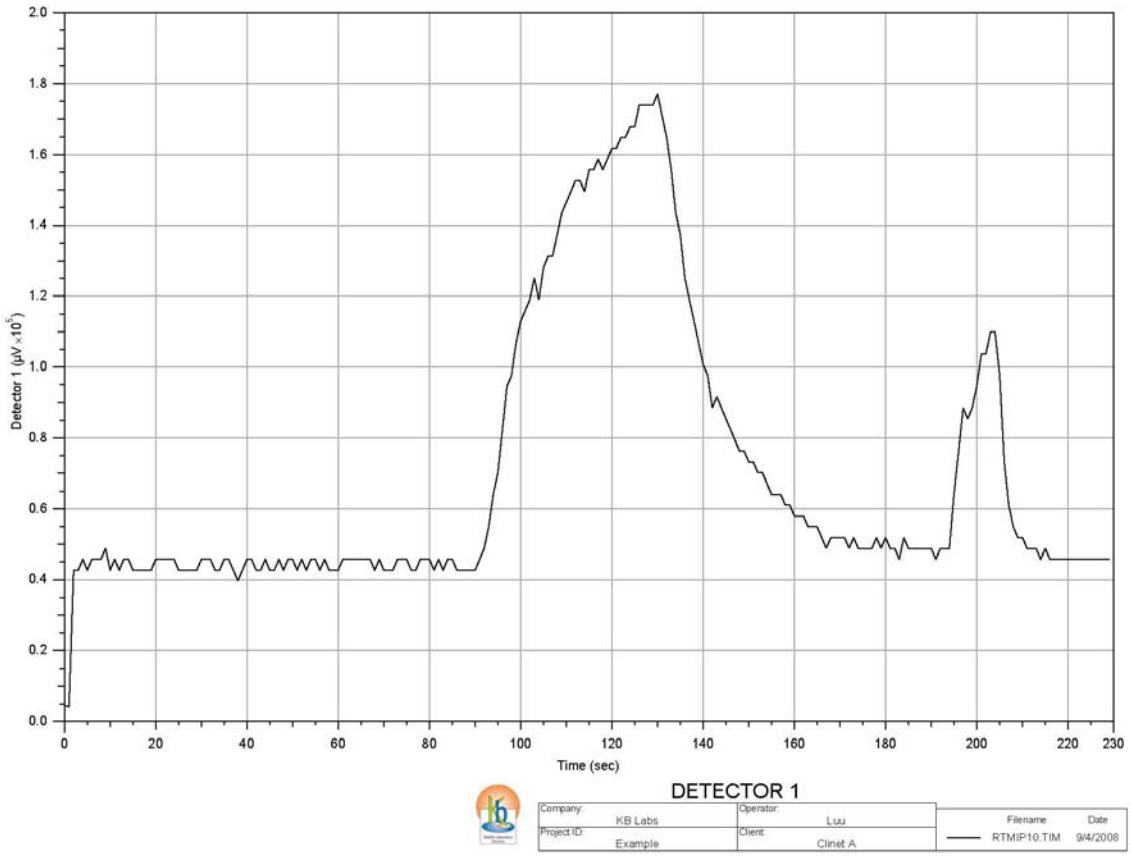

Figure 7. Response Test
This log shows a response test of the PID detector. The MIP probe is placed in a solution containing a known concentration of a target analyte and the response from each detector is logged, displaying response vs. time. In this case, a mixed solution of both a chlorinated and non-chlorinated compound were used and two peaks are generated. The time response is used to establish the travel time for the analyte to travel from the membrane surface on the probe through the trunkline and into the detectors. This time may be affected by the type of compound, gas flow settings, the length of the trunkline, and the composition of the line. Once the response is established, it is repeated throughout the logging process (before and after each log) to determine that the system is functioning consistently and there are no problems with leaks or plugs in the gas lines. Although a series of response tests at different concentrations can be performed "uphole" that will create a pattern like an analytical standard curve, it is not practical or recommended to use this type of information to attempt quantitation of the MIP data due to the variations in matrix conditions subsurface.

Log courtesy of KB Labs

Following the response test, the sampling probe is driven into the soil via a standard **direct-push technology (DPT)**. The depth of deployment is limited by the capability of the DPT rig in the site-specific conditions. The probe is functional in both soil and groundwater. Typical production rates are dependent on the subsurface conditions, but average about 200 to 300 logged feet per day.

Note that MIP is usually performed with DPT as the sampling platform, but it can also be coupled with a cone penetrometer (CPT) for greater definition of soil stratigraphy.

As shown before, the output is generally presented onsite via strip log style graphical representation showing all detector responses including the soil conductivity, speed of penetration and probe temperature. The raw data itself, which is collected continuously, can be imported into various software programs and used to generate two- and three-dimensional visualizations of the contaminant plume or mass. Adding the EC or CPT data in combination with the MIP logs may define the contaminant pathways..

The standard MIP probe has a built-in dipole for **electrical conductivity (EC)**. While onsite during logging for contamination, the operator can observe a conductivity signature change that indicates changes in soil classification.

The general assumptions are that conductivity increases as the grain size decreases (e.g., electrically conductive clay content increases) or moisture content increases.

Paired with the MIP-provided contaminant information, often a pattern is detected that gives an indication of defining sandy versus clay conditions. With chlorinated solvents, a significant contaminant concentration can commonly be viewed resting above a clay layer. Knowing where the clay is can also allow the operator to halt penetration and prevent puncture of a confining layer.

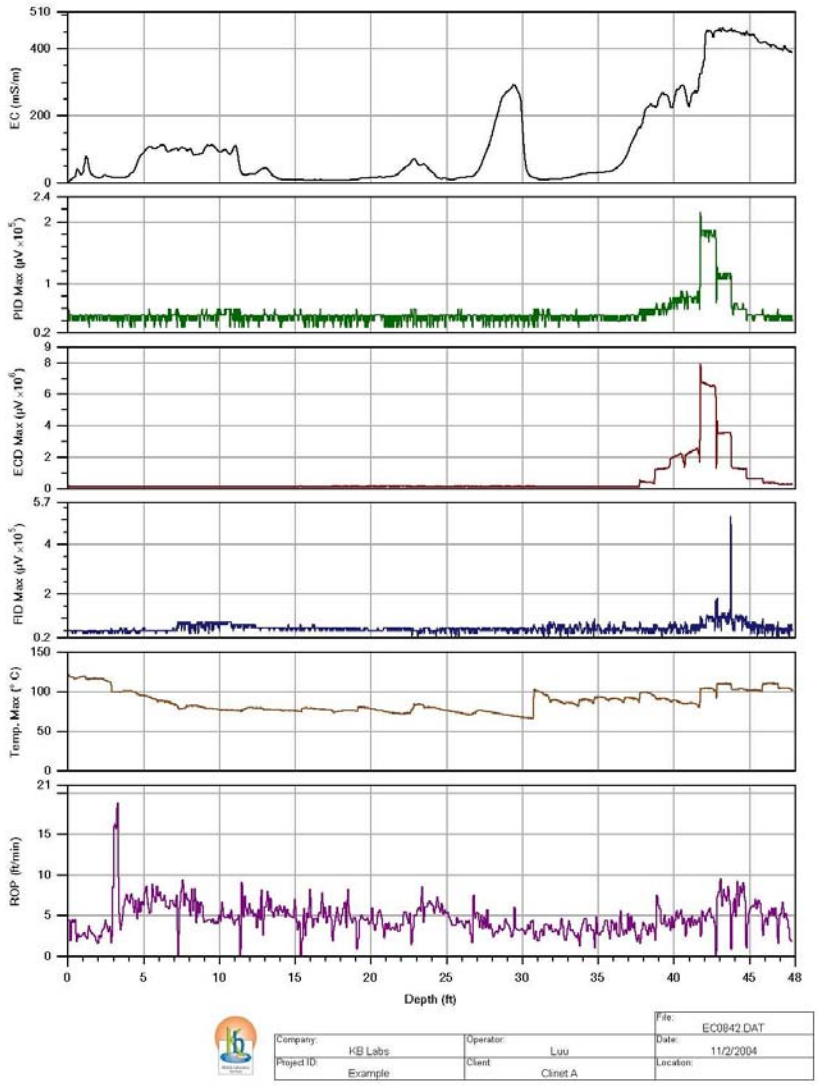

Figure 8. Chlorinated solvent in clay
This log is from a coastal site with chlorinated solvent contamination present at the beginning of a clay formation. The PID and ECD detectors are responding at the 40-45 foot interval and the conductivity signature is indicating the presence of finer material. On this particular site, all MIP logs indicated that the solvent was only detected in the 35-45 foot zone. This allowed the project manager to restrict subsequent sampling and laboratory analysis to the depths of interest.

Log courtesy of KB Labs

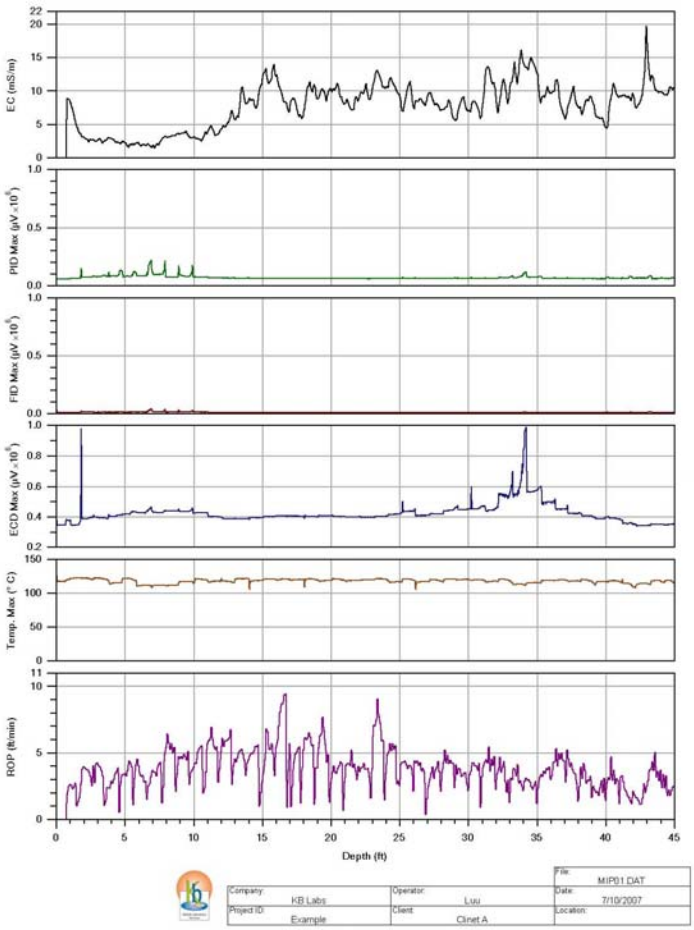

Figure 9. MIP in Sapprolite
Here is an example log of data taken in a heterogeneous sapprolite matrix. The conductivity signature in this case does not have a clear identification pattern. The chemical detectors are, however, providing valuable information on vertical distribution of contamination. Note the relatively low levels of chlorinated solvent responses in the 25 to 40 foot interval. Also, there is contamination present in a shallow zone of low conductivity between 4 and 10 feet. It is possible this is a backfilled area. Since all detectors are showing response, there could be a petroleum presence. This is an example of where targeted confirmatory sampling would be beneficial.

Log courtesy of KB Labs

How the MIP is used

By using the MIP system during a source area characterization investigation, soil sample collection can then be focused at locations exhibiting **non-aqueous phase liquid (NAPL)** characteristics, significantly reducing time in the field.

The MIP system is often used for point source location. It is an excellent tool for multiple point source sites that might otherwise require many sampling sites when using traditional methods. In other words, the MIP enables field teams to avoid a “swiss cheese” approach and offers the site manager enough real time information to effect appropriate changes in the sampling plan on a daily basis.

The MIP system allows rapid correlation of lithologic changes and contaminant distribution. It works in both saturated and unsaturated zones and is effective in locating DNAPL in the subsurface. Besides point source location and plume chasing, there are other site conditions that benefit from the use of the MIP.

For sites with a known point source, such as a typical dry cleaning candidate site, the MIP can be used over a one- or two-day period to vertically delineate the resultant plume. The investigator can then limit the vertical portion of the continuing sampling effort, eliminating unnecessary sampling while continuing to define the horizontal plume using direct push sampling and a mobile analytical laboratory.

The MIP can be used to further define and fine-tune a planned injection, and can return for a comparison look at post-injection subsurface conditions. By providing better definition of the contaminant distribution in

the source area, where the predominant portion of the contaminant mass resides, a day or two of MIP work in the contaminant source area provides, in conjunction with other site assessment data, generates valuable data for remedial design, including lithology and relatively high-resolution contaminant mass distribution. These data can be used for placement of injection or recovery wells, to select screen or injection intervals, and to choose locations for additional monitor wells.

The EC data produced in conjunction with the MIP is affected by chemical content and mineralogy of the subsurface. This property lends itself to using the EC data in conjunction with MIP data to detect and evaluate the actions of chemical injection. Following the injection, the EC/MIP can confirm product distribution and determine the radius of influence of the injected material.

Injected fluids generally have at least one physical property that is significantly different from the natural subsurface materials. They are also usually delivered from a specific point without dispersing throughout the subsurface volume, and usually enough injectate is delivered so that it comprises a significant portion of the pore volume.

A two- or three-order of magnitude higher signal from injection fluid over background is often seen in a subsurface location that has successfully received remediation chemicals. “Spikes” in conductivity may be observed, which would indicate product distributed only at discrete intervals.

By comparing logs taken of the target area before and after the injection, a comparison of both contaminant response and EC background change can

indicate the effectiveness of—as well as locate problems with—the injection.

The importance of being able to cost-effectively determine that injection fluid has been distributed properly in real-time is significant.

If the correct remedial approach has been made for the site, the single most important aspect of successful in-situ remediation is ensuring that the chemical contacts the target. The EC and MIP data can bridge the gap between the application or injection point and the observation point data, which is usually obtained from a limited number of wells.

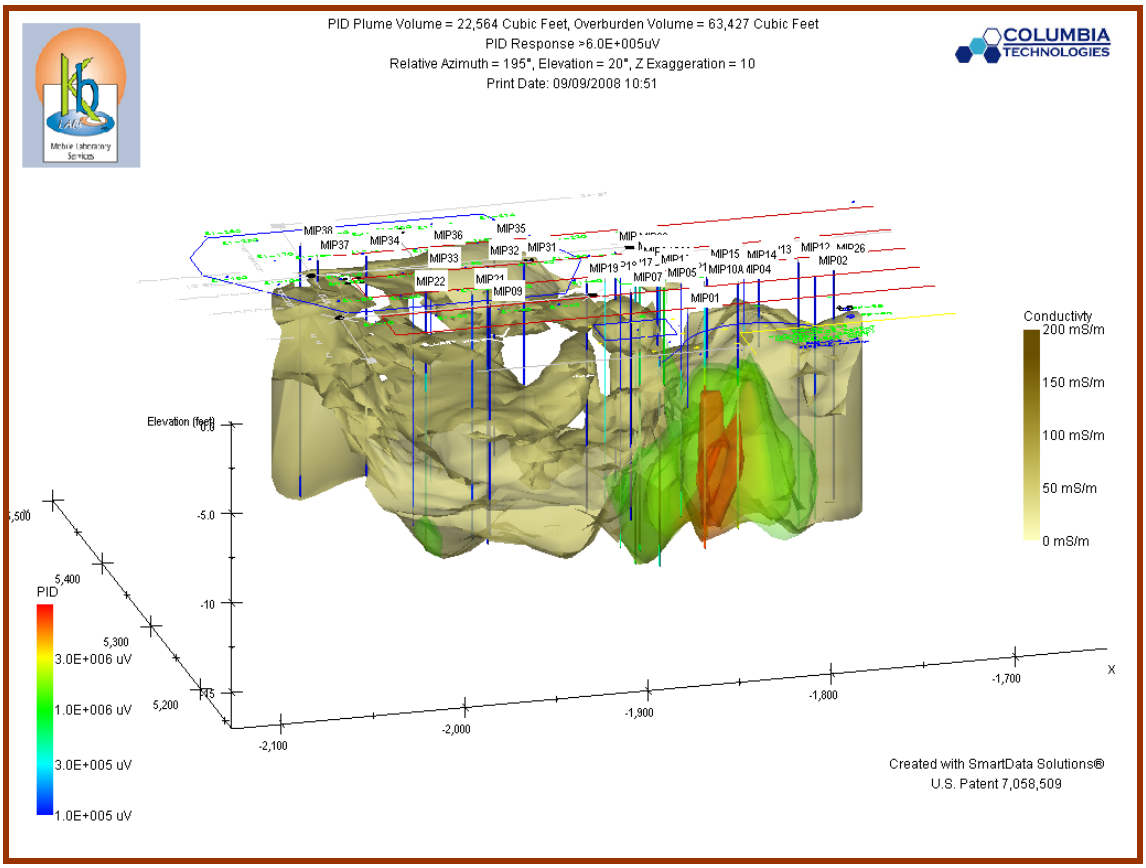

Figure 10. 3D Visualization
Due to the density of data output from the MIP, images like this can be created with a detailed visual representation of contaminant mass.
Image courtesy of Columbia Technologies and Kb Labs

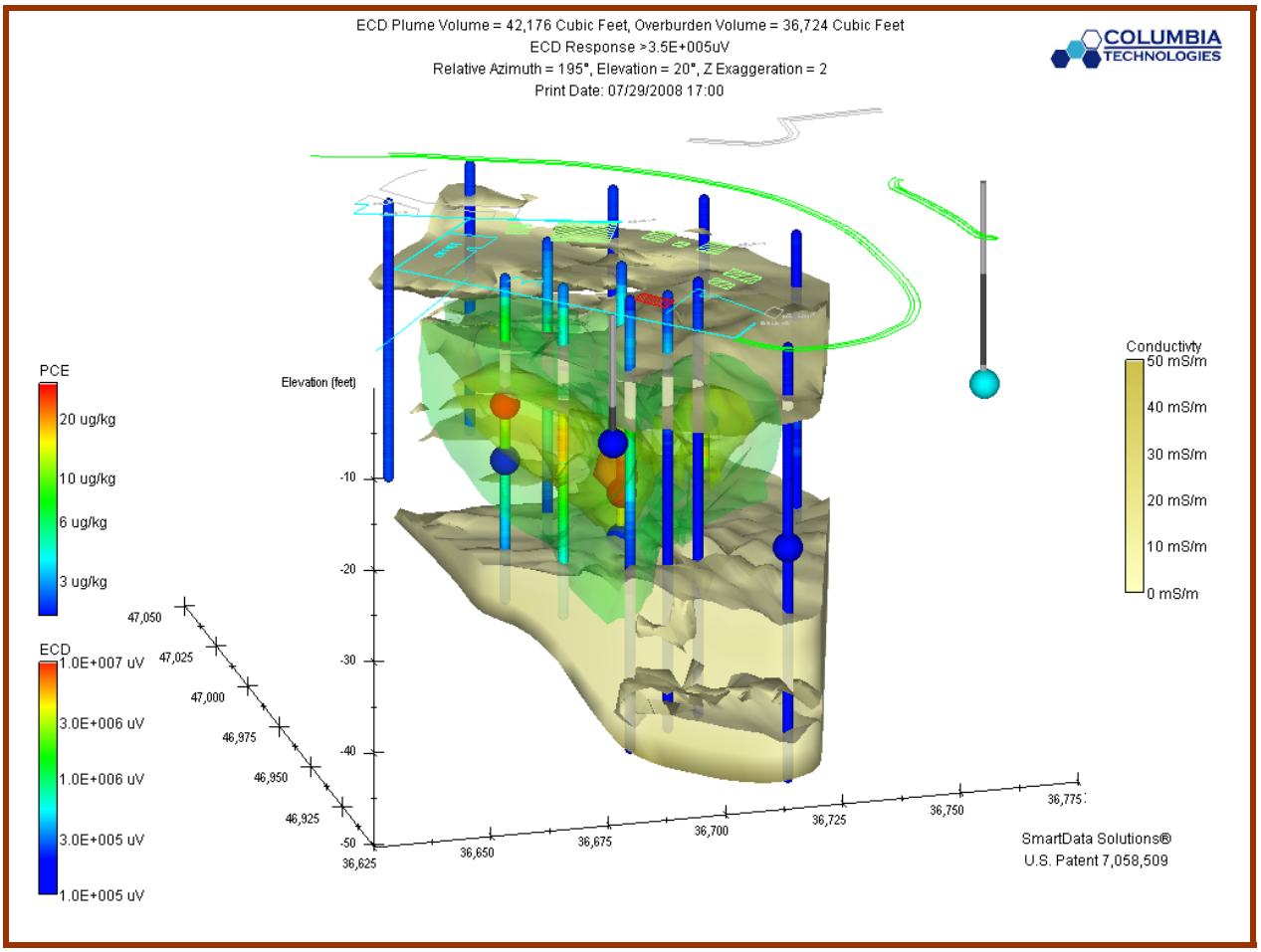

Figure 11. MIP and Lab Data
In this image, visualization of the Electron Capture Detector (ECD) responses are shown with corresponding discrete laboratory PCE analysis concentrations. Combining the information creates a collaborative data set and greater insight into the plume definition without a lot of sampling. With an onsite mobile laboratory working in tandem with the MIP and web-based data transmission, this can be achieved in a single mobilization.
Image courtesy of Columbia Technologies and KB Labs

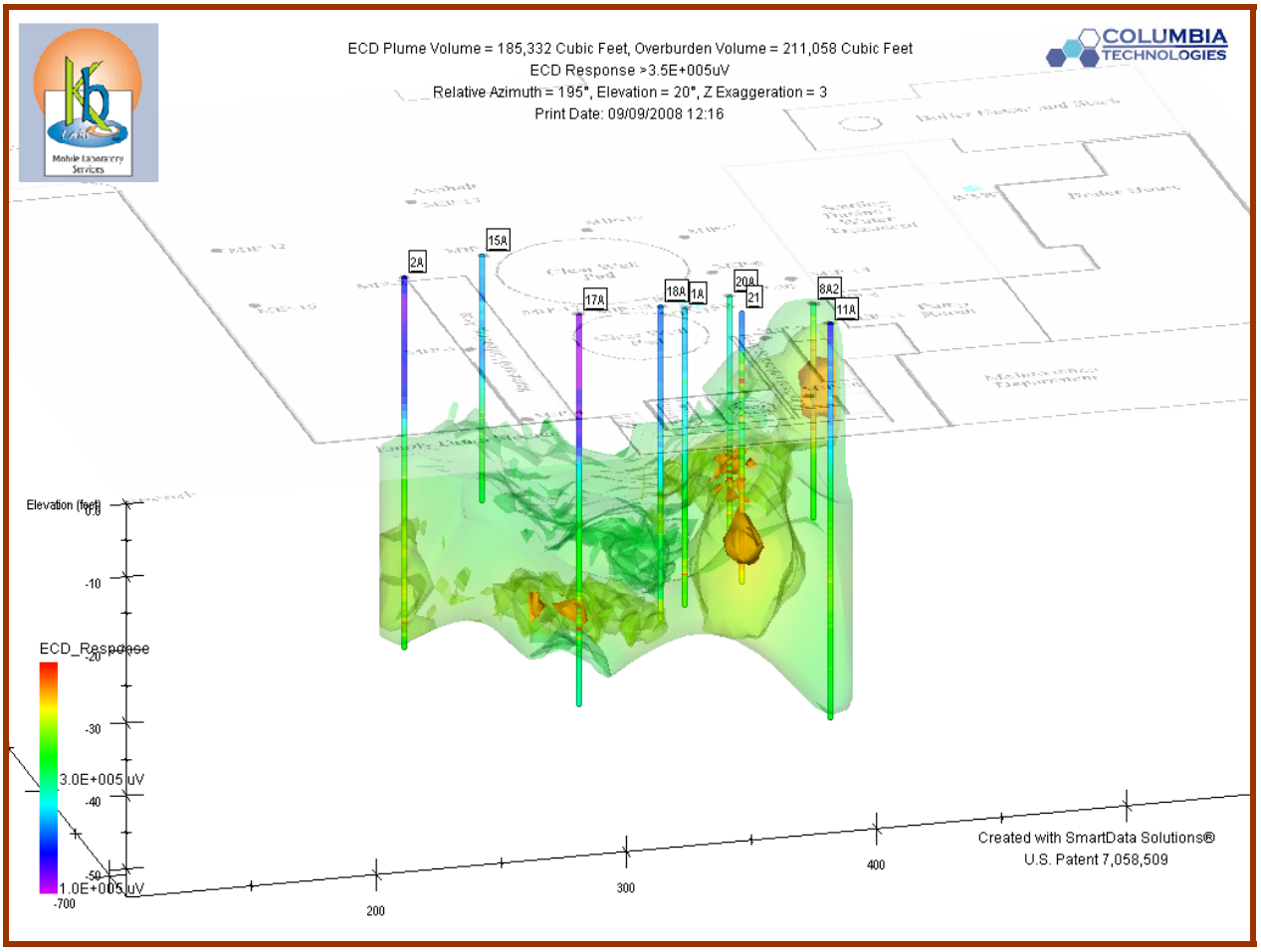

Figure 12. MIP Pre Remediation
This is a view of a contaminant mass created during a site assessment using the MIP
Image courtesy of Columbia Technologies and KB Labs

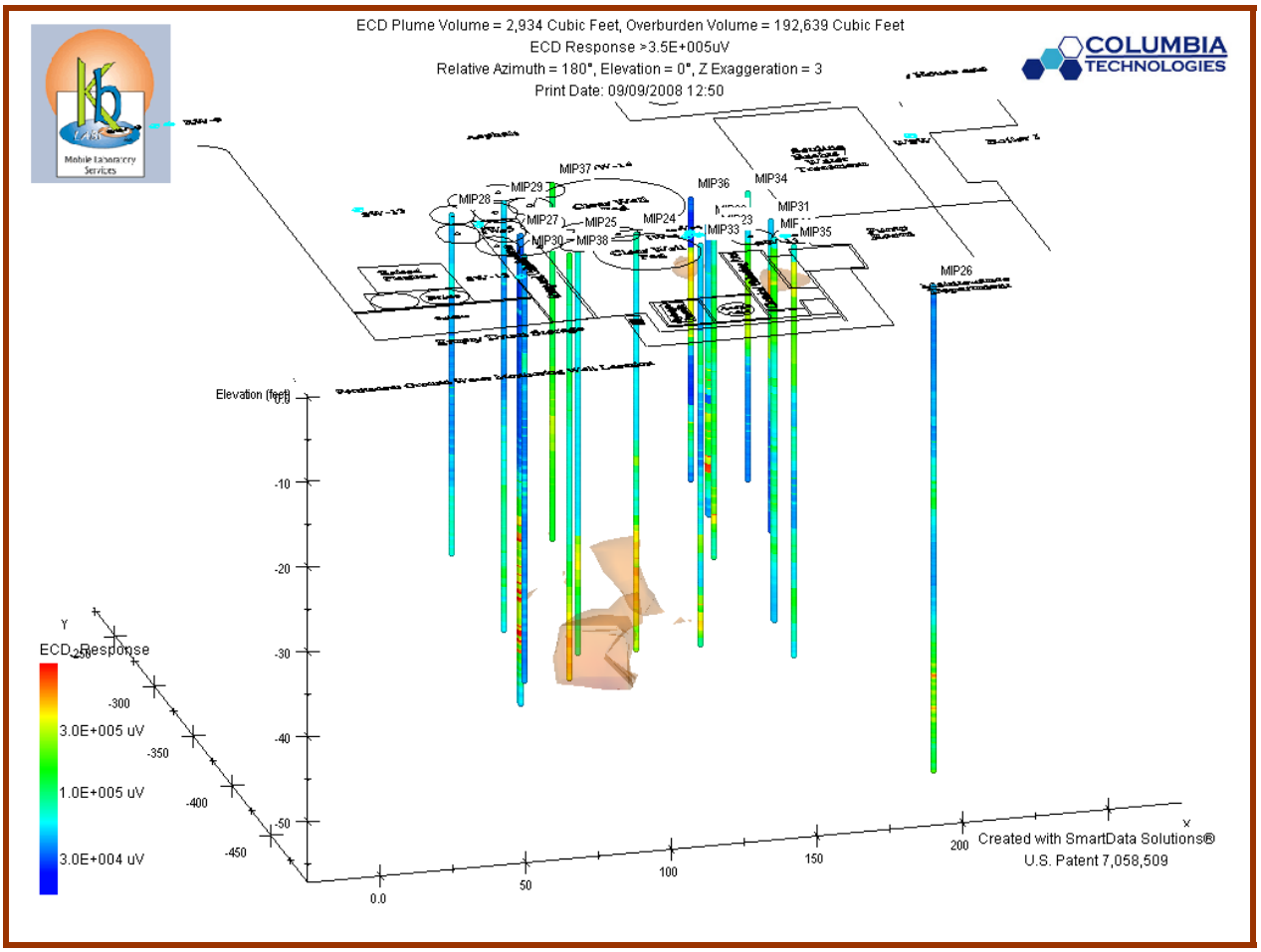

Figure 13. MIP Post Remediation
Following a persulfate injection, the MIP was redeployed to the same site to provide diagnostic information regarding the remediation process. This is the resulting view.
Image courtesy of KB Labs and Columbia Technologies

Limitations affecting MIP usage

Figure 14. MIP Rig in the Field

Photo Courtesy of KB Labs

There are limitations to the use of the MIP that need to be kept in mind:

- **The technology is limited to volatile contaminants**, so other technologies must be used at sites where significant quantities of semi-volatile or non-volatile contamination exists.

  Without separate trapping or a customized analytical system, the responses are only seen as total VOCs rather than being speciated into individual compounds. This drawback is

mitigated somewhat by the MIP's ability to distinguish between chlorinated and light petroleum (BTEX) plumes.

- Another complicating factor is the fact that **the MIP does not provide actual concentrations**. Confirmatory sample data may be used where appropriate to help interpret the MIP responses semi-quantitatively.

- **Carryover, the retention of contaminant in the membrane and trunkline, can occur in extremely high levels of contamination.** This may result in a false positive at subsequent depth readings, or an elevated gas phase detector baseline.

The careful engineer will bear these limitations in mind while designing, implementing and monitoring a remediation plan but, judiciously used, MIP is a useful tool in minimizing remediation costs, in both time and money.

Conclusions

Successful environmental remediation depends on developing the most accurate possible image of subsurface conditions. The membrane interface probe is a tool that is useful when assessing the severity and extent of contamination in soils and groundwater in-situ. The ability of this technology to sample dynamically, providing data necessary for informed decision-making while still in the field, makes it a key strategy for the informed site manager.

References

1. Crumbling, D., Summary of the Triad Approach, U.S. Environmental Protection Agency, Office of Superfund Remediation and Technology Innovation, Washington, DC, 2004.

2. , ASTM Designation D7352-07: Standard Practice for Direct Push Technology for Volatile Contaminants, 2007.

3. Geoprobe® Systems, http://www.geoprobesystems.com

4. Columbia Technologies, http://www.columbiatechnologies.com

5. KB Labs. http://www.kbmobilelabs.com